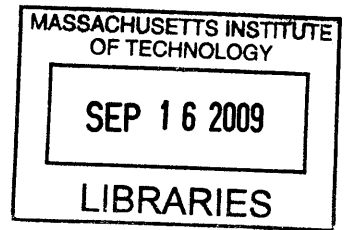


Frontal Collision Analysis of City Car

By

Terance Neal
David Hill




SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF


BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

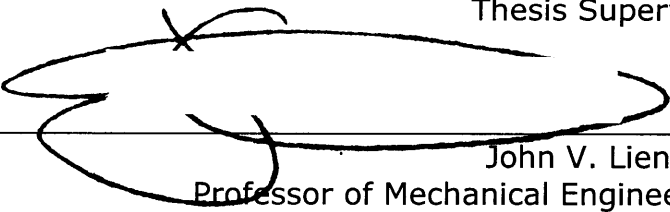
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JUNE 2009

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Submitted to the Department of Mechanical Engineering
on May 11, 2009 in Partial fulfillment of the
Requirements for the Degree of Bachelor of Science in
Mechanical Engineering

Abstract

This experiment tests the proposed crash system of the CityCar. The car is to fold during the crash to help decrease the impact force experienced by the passengers. The experiment was conducted by running a simulation of the car crashing into a wall compared to that of a rigid car with no folding, and by building a one-fifth scale wooden model of the CityCar, running it into a wall, and measuring the force upon impact. The simulation was ran at 20mph, 50mph, and 80mph, with weight ratios between the front and back of the car respectively of 1:1, 1:2, 1:3, 2:1, and 3:1, as well as three variations in the damping of the folding process. Both experiments show that the folding car experienced lower forces than the rigid car. The variations done in the simulation suggest that a back heavy car with considerable damping is best, but these results were a bit inconsistent and unclear and, therefore, will be tested more completely in the future. Results suggest that folding during a crash provides significant help, but this experiment only provides preliminary feedback useful for future analysis of the CityCar.

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Introduction



Figure 1: CityCar concept

Recently, society has started to push toward a cleaner environment. This has sparked many new ideas and innovations for more solutions to the environmental problems that currently exist. One major contribution to pollution is by the cars we drive every day. Some solutions to this problem have been in hybrid cars, which use gas and electricity, and electric cars.

Companies have also started to make cars smaller to address this problem, as the lighter vehicles are usually more fuel efficient. An example of this trend is the SmartforTwo car, a small, compact car with low emissions of carbon dioxide. The car, built for urban transportation, has a smaller footprint than most cars, making it easier to maneuver in urban settings and easier to park.

The need for more ecological products gives rise to a new idea: the CityCar. The CityCar is an innovative concept vehicle being developed at MIT that utilizes some of the established

ideas of environmentally friendly vehicles. The car is smaller than the average and runs solely on an electric platform. Like the SmartforTwo car, it is built for urban environments, thus, its small size makes it easier to navigate through the city. The end goal of the CityCar team is to have multiple CityCar stations in metropolitan areas to provide for convenient and efficient mobility on demand. Pedestrians will then be able to rent out a CityCar from one of these locations to use and return it to the station, or even to a different station. This is a similar set up to the Zip Car program, where members are able to expeditiously rent a vehicle from any location; nevertheless, the CityCar mobility on demand program allows the user to engage in a more dynamic one-way sharing program similar to the *Velib* bicycle sharing program in Paris. This set up, paired with environmentally friendly vehicles, could prove to substantially lower vehicle pollution and congestion.

Although smaller, lighter vehicles help address concerns of pollution and congestion, it creates an issue with passenger safety. While smaller cars prove to be more efficient, bigger cars prove to be safer. Since the car will be significantly smaller, it needs to be uniquely engineered to meet safety standards. Most cars rely on an excess of material in the front in crashes. The deformation of the material during a crash provides deceleration for the passenger during the crash, which takes away from the initial impact. The CityCar does not have this extra material in the front, so the front impact on the car during a crash is the biggest concern. This problem will be explored through research of crash parameters and statistics of existing cars, and by utilizing the design of the CityCar to incorporate specific factors that will make the car crash worthy.

City Car Design and Architecture

The design of the CityCar is very unique. It exploits its full electric power train to incorporate a highly modular platform in which all drive components (motors, steering, suspension) are packaged local to the wheels. This modular platform gives design flexibility to the vehicle for new features, such as the ability to fold and reduced its parked footprint in half.

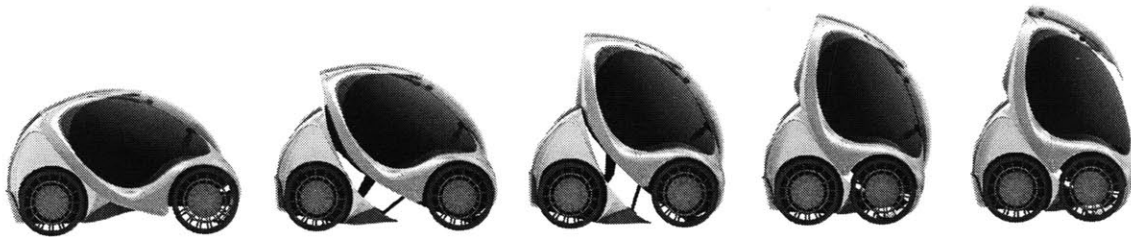


Figure 2: Profile of CityCar folding

This makes the vehicle more compact for storing purposes, given that the goal is to set up multiple cars for use in different cities. Because the car also utilizes in-wheel motors with no engine in the front, this allows for a distinctively large cabin, giving passengers more room without compromising the small frame of the vehicle. Probably the most innovative design specification of the CityCar is that it does not contain a dashboard or steering column. The car uses a drive-by-wire system, where the passenger uses joysticks to steer the vehicle.

For the crash analysis in this study, the design specifications that will play a role are the small front compartment of the vehicle and the folding capability of the vehicle. Given that the front of the vehicle has less material than the average car, the front of the CityCar will have to be

tougher than that of the common car. This is necessary to save the integrity of the cabin and protect the passengers. This means that the front panel of the CityCar is designed for minimal deformation. This assumption will be made for the purposes of the analysis in this experiment.

The folding mechanism is also a factor for the CityCar during a crash. The front panel of the car will be tough to prevent deformation, but this deformation helps to lessen the impact on the passengers during crash in an ordinary car. To compensate for this missing element, the CityCar will be designed to fold up upon impact in the event of a collision. Assumedly, some of the impact will go into the dampened folding of the vehicle naturally. The specific dampening of the folding process can be optimized through testing, given for a happy median between efficient folding and crash assistance. The folding can help to provide the deceleration to the passenger lacking from the compact front panel of the vehicle.

These are the factors tested in the experiments and crash analysis of the CityCar prototype. This was done using a digital simulation of the CityCar crashing into a wall at varied speeds, weight distributions, and fold damping coefficients, and by crashing a one-fifth scale model into a wall. While the design specifications are all but finalized for the design of the CityCar, the variation of these parameters for crash testing allows for alteration to the parameters or even implication of new specs depending on the results of the testing. By running test both virtually and empirically, we look to illustrate that we can utilize the CityCar's ability to fold to provide for a dynamic crash structure – allowing us to decelerate the passengers at an acceptable rate in a front impact scenario.

Precedence: Existing Crash Parameters and Statistics

Preventing fatalities from car collisions is of extreme importance. Since 1994, there has been a yearly fatality rate of over 30,000 fatal crashes taking over 30,000 lives in the USA alone. Of the car collisions that occur, approximately 60% of collisions are frontal collisions. Because of the high amount of frontal collisions that occur, it is imperative that cars have many safety features which guard the driver and passengers when experiencing a frontal car collision.

Studies have been conducted to measure the amount of force the human body can withstand without sustaining serious damage. Colonel Stapp, in an effort to increase the G-force limit imposed on air force pilots, underwent several tests on a rocket propelled sled. The track mounted sled used multiple stage rockets and powerful water brakes to exert incredible amounts of force on the passenger in a manner very similar to that of a car crash. As he withstood G forces between 18G and 35G, his body started to get negatively affected. He withstood a maximum force of 46.2G, in which he suffered a complete red out (blood rushed to his eyes and broke capillaries and caused hemorrhaging) and was barely conscious. Large forces definitely take their toll on the body, with extremely high forces causing death. According to the NHTSA, experiencing 65G + of force on the body can result in death.



Figure 3: Image of Smart Fortwo frontal crash test. Crumple zone absorbs majority of energy in collision.

Because the CityCar is of such compact size, it is best to study the crash data from other miniature and compact cars and relate this to how the CityCar would perform, as opposed to studying data from full size vehicles. The 2009 Honda Fit, weighing 2,546 lbs, received overall good performance ratings for front, side, and rear tests; the 2007-09 Toyota Yaris, weighing 2,377 lbs, received a yellow rating for the head/neck injury rating and green ratings for the rest; the Smart Car, weighing the least of the three at 1,797 lbs, received a yellow rating for head/neck and leg/foot right injury measures, and a green rating for a chest and leg/foot left injury measures. The ability to take these forces is mainly due to the crumple zone that is present in all of these vehicles, coupled with the still substantial size of the vehicles. Data suggests that as the size of the vehicle decreases, the level of safety present in the vehicle follows suit; for vehicles 1-3 years old during 2006, mini-cars experienced 106 driver deaths per million registered vehicles compared with 69 driver deaths in large cars. The data from the three smaller vehicles also

support this data, as trends can already be noticed between the size of the car and the level of safety present.

The CityCar lacks a crumple zone, so it must rely on its folding mechanism to absorb some of the energy from the collision.

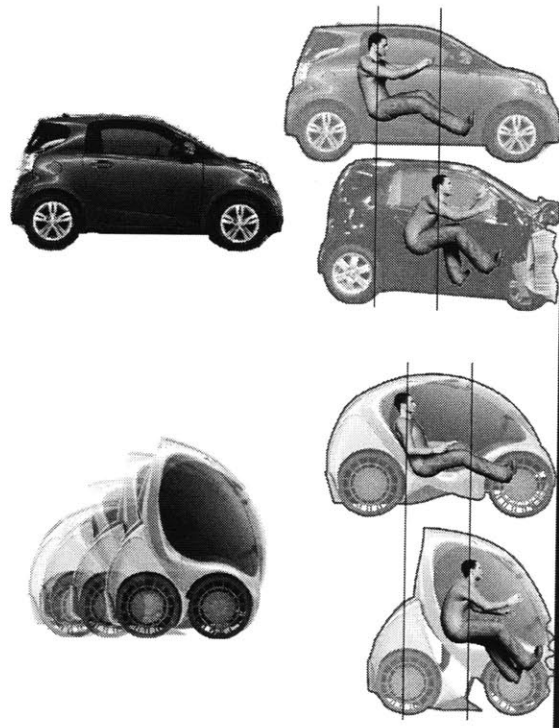


Figure 4: Normal vehicle utilizing on crumple zone in frontal collision, and CityCar utilizing folding mechanism.

CityCar Crash Theory

The history of car crashes helps to give a foundation of general safety standards for drivers, but in order to make the CityCar comparably safe, the theory involved in vehicular collisions must be understood. Dynamics explain the physics of a car crash. Said physics are then correlated to what the human body can withstand. These considerations gives the precautionary methods that exist today, which mainly include car crumple zone, seat belts, and air bags. There is no way to make cars completely safe in all scenarios, but today's measures have been optimized fairly well, and, with smart and alert driving, can prevent vehicular fatalities.

The dynamics of motion are broken down into three main factors: position, velocity, and acceleration. The position is where an object is at a given point in time, where the velocity is how fast that position is changing over time, and the acceleration is how fast that velocity is changing over time. A car on the road will have a position, velocity, and acceleration at every given point in time. More specifically, the car's velocity and acceleration are the significant factors of the car's dynamics when approaching a collision. Upon collision, the mass of the car adds another important parameter. During a collision, there is a transfer of momentum between the car and its collider, where momentum is $P = mv$. Through the law of conservation of momentum, we know momentum is conserved, so all the momentum of both objects must be transferred during the collision. The conservation of momentum is what determines the effects of a crash.

To expound, given that momentum must be conserved, we know that the total momentum of a system at one state must equal that of any other state unless outside forces act on the system. This gives: $mv_{total1} = mv_{total2}$. What this tells us is that the effects of a crash are dependent

on the mass of the two objects and their velocities. This gives us the instantaneous dynamics of a car during a collision. From here, we can determine the forces on the car and its acceleration during the crash, as well as that of the driver. The worst scenario for a collision is a car crashing into an immovable object, such as a wall. This would mean that all of the car's momentum is transferred back into itself, leading to a drastic impact force and acceleration.

The dynamics experienced by the car are ultimately transferred to its occupants as well, which is why it is so important to understand effects of a collision. A collision leads to a very sudden change in speed and acceleration through momentum transference and impact force. This impulse will also be felt by a driver. A human can be killed by an impulse if it is too strong. A person cannot accelerate or decelerate too fast because it would kill them, so it is important for a human to be able to withstand the forces and dynamic changes during a collision. To ensure this, cars must be tested for certain crash safety standards, as discussed earlier.

Cars are tested by crashing them into walls. This allows for car dealers to make the car as crash worthy as possible. In normal cars, its crash capability can be controlled through the material properties of the car, and its size and mass. The material of the car would need to be strong, but ductile and elastic, so that it can deform. The crumpling of the car's front panel absorbs some of the force experienced by the car during a collision, so the material should be optimized for this effect. This crumple zone is one method of making a car safer than most cars have nowadays.

The crumple zone is the only way to lessen the dynamics of a car during a crash that is presently known, so other factors that commonly keep passengers safe are seat belts and airbags. Seatbelts stop the passengers from flying forward inside the car, possibly flying through the windshield. The motion of the passenger during the collision would want to be kept at a

minimum to prevent the passenger from injury by being slammed into things inside the car. Airbags are intended to slow down the momentum transferred to the passenger and provide cushion upon impact.

Although crashes are often fatal for its victims, today's standards help to save the lives of many more crash victims who survive. These standards must be met by normal cars, which rely on the crumple zone, material properties, seat belts, and airbags to save the lives of its passengers. The same must be done for the CityCar.

The theory behind a collision for the CityCar is a bit different from that of a normal car due to its unique design. The CityCar has a very limited amount of material in its front panel for deformation, so for safety purposes, it is best to design this material for little to no deformation. This deformation is a dependent factor for collisions of normal cars. As presented before, it is proposed that this lack of deformation be made up by the folding of the car during the collision. A sensor will be placed on the front panel so that the folding mechanism unlocks before impact. The CityCar will still have seatbelts and airbags are optional, so this is the only change.

To see why folding would be a suitable alternate method, we must look at the dynamics during folding. We know about the impact forces and momentum changes during a collision already. This effects act upon the crumple zone of the car, so the crumpling of the car takes away from the overall force felt by the car as a whole. This works the same way for the folding process. The initial impact will be translated into the folding of the car until the car has folded completely, upon which the entire car will experience the remaining impact. Since the car is, in a way, rotating about its own axis, it helps to absorb some of the transferred momentum as rotational kinetic energy. Theoretically, the rotation would not prove to be dangerous for the

passenger and would not create a big impulse on the passenger or car, so it would result in the dampening of the impact itself.

Not only will the rotational distance of the folding play apart, but so will the dampening factor of the folding. In other words, part of the CityCar design will be to discover how much force is required to fold the car. It is the same effect as putting a rotational damper on the car. This rotational dampening would lead to more force absorption during a collision. This factor has to be optimized because too little damp will make the car fold quickly and will not change the impact too much, but too much damp will prevent the car from folding and translate the momentum throughout the entire car. If the theory is correct, the folding mechanism paired with the appropriate dampening constant will make CityCar crash worthy and safe to drive.

Digital Simulation: Experimental Setup

To test the CityCar crash theory, a 2-D physics modeler was used to simulate the CityCar crashing into a wall. The program used is called Working Model. The experiment was setup by drawing an object very similar to the shape of the CityCar. The car is created by creating the front and back of the car as separate objects and connecting the two with a rod and a beam with pin joints, so that the car can fold. A rod and beam were used to imitate the 4-bar linkage system that the CityCar utilizes to fold. This was done for simplicity, yet remains a reliable test source. Two cars were used to test: one that was rigid and could not fold, and the folding car. The comparison of the two will help to show whether or not the folding of the car during a collision makes a difference. The two cars were crashed into an immovable wall for testing. Each car was tested at three speeds, 20mph, 50mph, and 80mph. The total mass of each car is the same at 1032kg, where the front and back total 1000kg and the wheels are 16kg each. Although the CityCar concept is targeted for roughly 500kg, the digital simulation was done for comparison purposes, so as long as the rigid car, used as a control, is the same as weight as the test car, the comparative analysis should prove suitable.

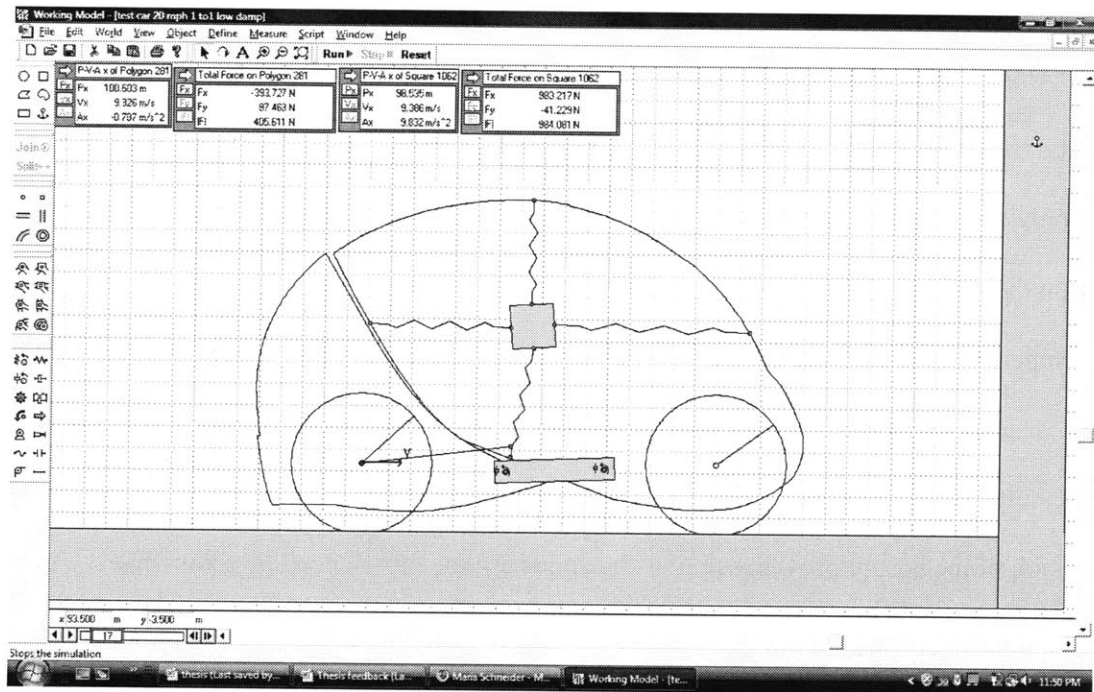


Figure 5: Screenshot of the CityCar digital simulation

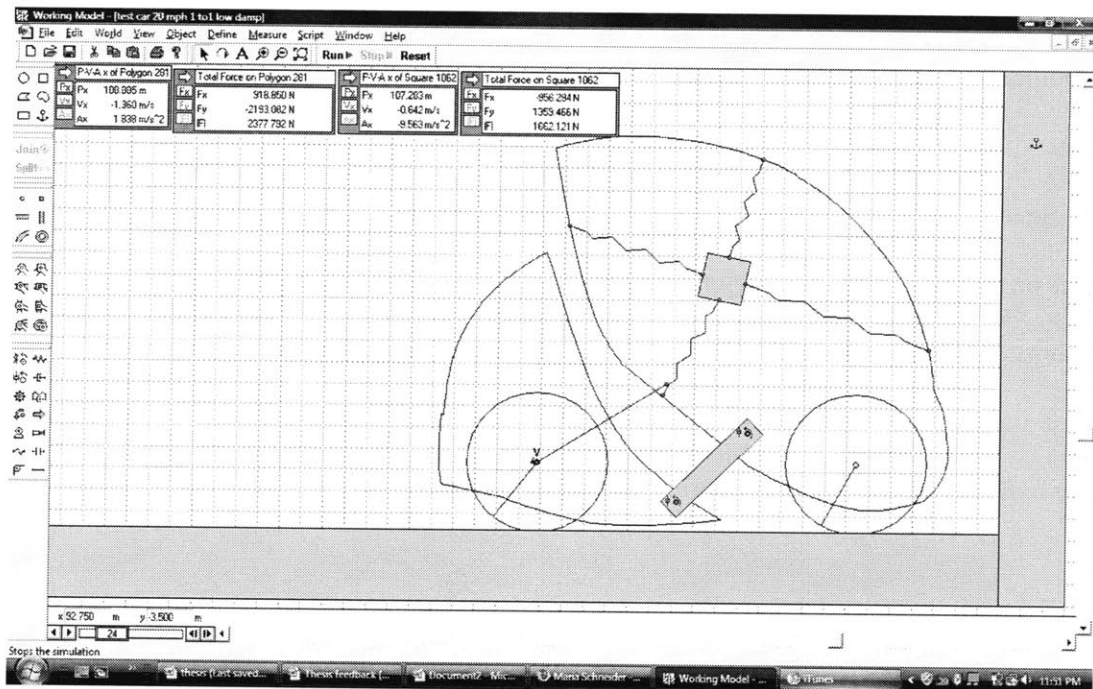


Figure 6: CityCar test car after colliding into the wall

Along with varied speed, the test car was tested with different weight ratios between the front and back of the car and with different damping constants of the folding mechanism. This is to not only test if the folding makes a difference, but to see which parameters impact the folding effect on the collision impact. The front to back ratio was varied at 1:1, 1:2, 1:3, 2:1, and 3:1. The dampening constant was varied with low damping, some damping, and high damping.

Inside of the front half of each car is a 100kg square with four springs attached to it from the top, bottom, left, and right. This is to simulate the effects on a passenger inside a car. The suspension of the square provides similar dynamics as that experienced by a passenger with a seatbelt in a car. During each test on each car, the position, velocity, acceleration, and force in the x-direction was measured for the front half of the car and for the square suspended inside the car, denoted as the driver. The control car was only run at the three different speeds, while the test car resulted in 45 different variations between weight ratio, speed, and damping constant. The implications of the simulation come from comparing the 45 test car runs with the 3 control car runs.

Several assumptions are made to validate this experiment. It is assumed that the physics modeler provides accurate simulation of real world dynamics and phenomena, such as friction and gravity. We also assume that the digital simulations of the crashes are imitative to that of real life. Lastly, we assume that the effects experienced by that of the suspended square are directly indicative to the effects experienced by a passenger.

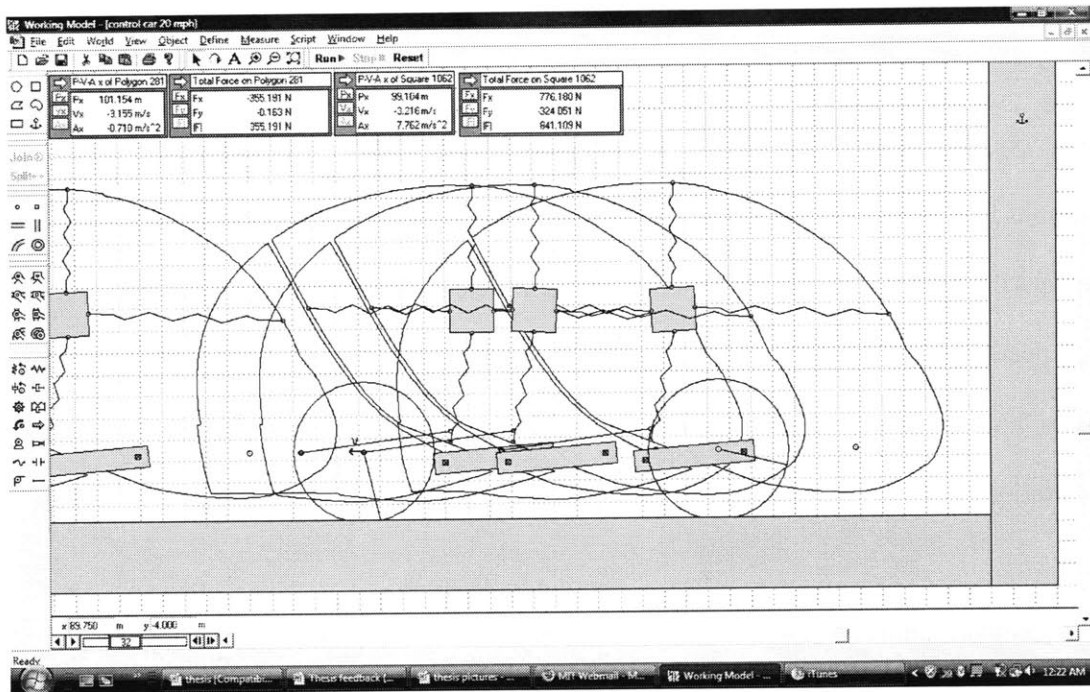


Figure 7: Profile of control car in simulation

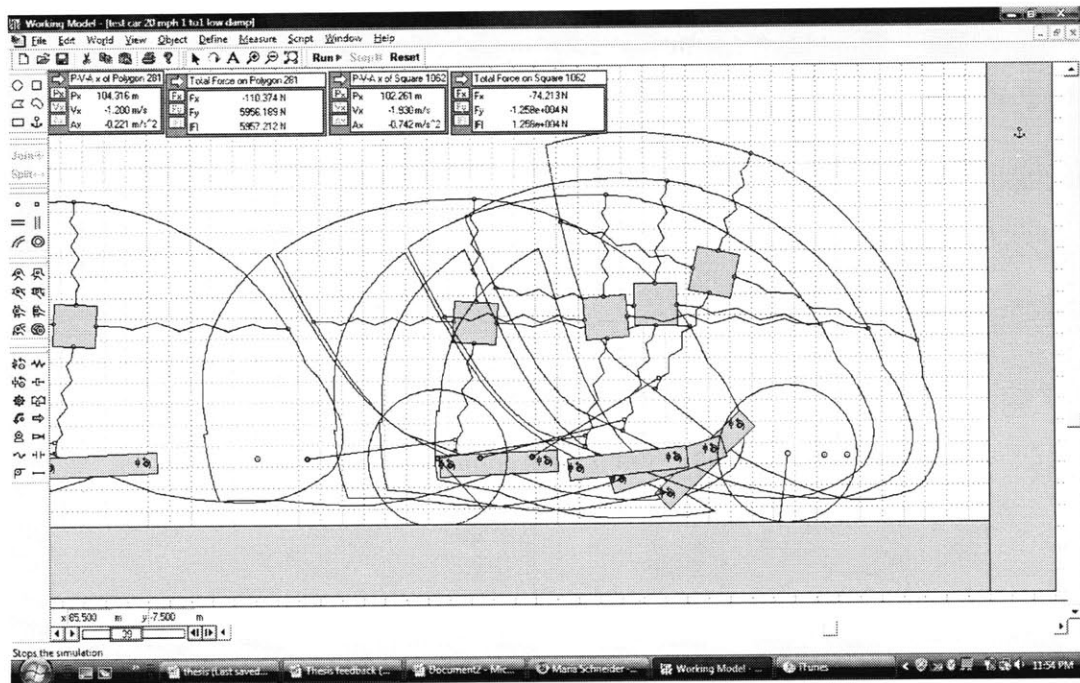


Figure 8: Profile of test car in simulation

Digital Simulation: Results

After several runs, the collected data, while varied and a bit inconsistent, had one common outcome: the folding test cars proved to provide less impact on the car and driver than the completely rigid control car, as seen in Tables 1, 2, and 3. Figures 9 and 10 show how significant the difference between the control and test car is in most cases. Most runs of the test car had decelerations around 75% that of the control car, for both the car and driver. The data becomes more complicated when taking the varied weight ratios and damping constants into consideration.

Simulations at 20mph				
car	Weight Ratio	Amount of Damping	Peak Acceleration of Car	Peak Acceleration of Driver
control	1 to 1	none	93.506	350.044
test	1 to 1	low	73.071	277.433
test	1 to 1	some	77.412	285.584
test	1 to 1	high	74.12	259.509
test	1 to 2	low	77.054	267.529
test	1 to 2	some	69.759	271.711
test	1 to 2	high	72.831	261.607
test	1 to 3	low	69.466	262.947
test	1 to 3	some	84.053	253.524
test	1 to 3	high	66.962	270.91
test	2 to 1	low	72.765	289.749
test	2 to 1	some	70.301	299.11
test	2 to 1	high	67.837	298.775
test	3 to 1	low	78.096	297.533
test	3 to 1	some	70.929	304.618
test	3 to 1	high	64.785	313.609

Table 1: Peak Accelerations at 20mph

Simulations at 50mph				
car	Weight Ratio	Amount of Damping	Peak Acceleration of Car	Peak Acceleration of Driver
control	1 to 1	none	129.491	1360.979
test	1 to 1	low	104.611	868.161
test	1 to 1	some	104.67	924.386
test	1 to 1	high	159.244	968.186
test	1 to 2	low	162.964	880.414
test	1 to 2	some	181.459	779.048
test	1 to 2	high	126.767	862.044
test	1 to 3	low	204.658	999.995
test	1 to 3	some	172.462	775.204
test	1 to 3	high	198.28	823.736
test	2 to 1	low	181.882	1101.957
test	2 to 1	some	163.114	1112.774
test	2 to 1	high	155.513	1004.81
test	3 to 1	low	92.596	1016.98
test	3 to 1	some	154.048	966.384
test	3 to 1	high	88.5	935.592

Table 2: Peak Accelerations at 50mph

Simulations at 80mph				
car	Weight Ratio	Amount of Damping	Peak Acceleration of Car	Peak Acceleration of Driver
control	1 to 1	none	201.456	1986.882
test	1 to 1	low	222.242	1492.444
test	1 to 1	some	231.979	1514.778
test	1 to 1	high	152.984	1419.933
test	1 to 2	low	318.105	1379.644
test	1 to 2	some	141.829	787.659
test	1 to 2	high	265.946	1407.65
test	1 to 3	low	389.223	1272.2
test	1 to 3	some	340.519	1367.192
test	1 to 3	high	183.289	768.752
test	2 to 1	low	203.031	1739.283
test	2 to 1	some	193.012	1647.464
test	2 to 1	high	176.616	1520.667
test	3 to 1	low	190.13	1731.747
test	3 to 1	some	142.104	1507.202
test	3 to 1	high	159.057	1581.274

Table 3: Peak Accelerations at 80mph

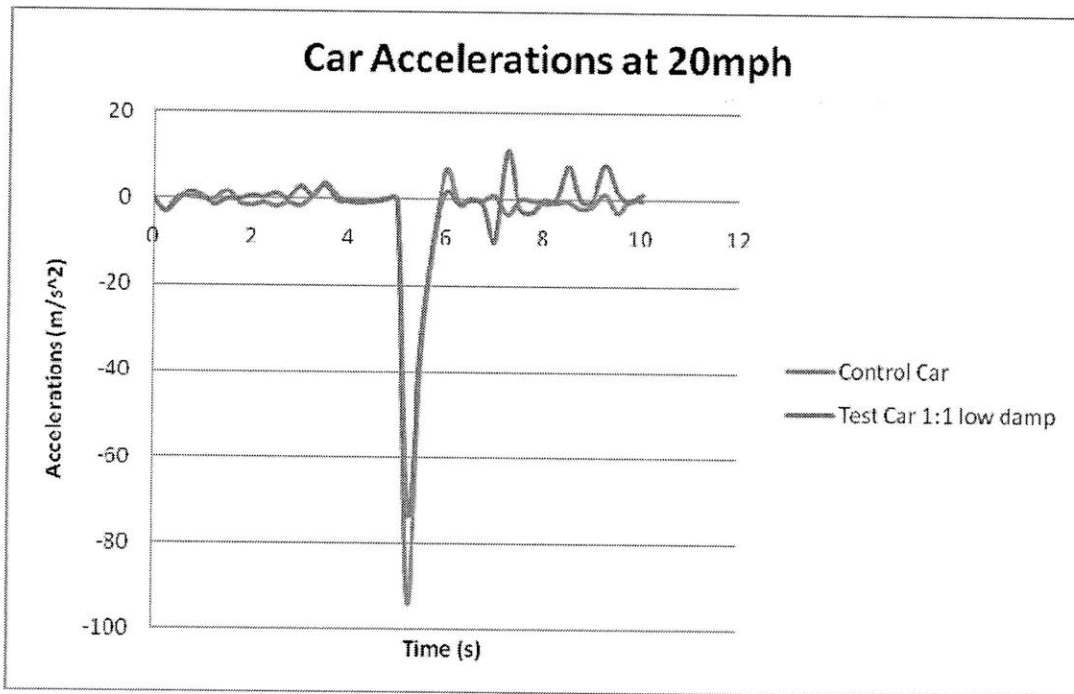


Figure 9: Car accelerations of control car and test car at 20mph

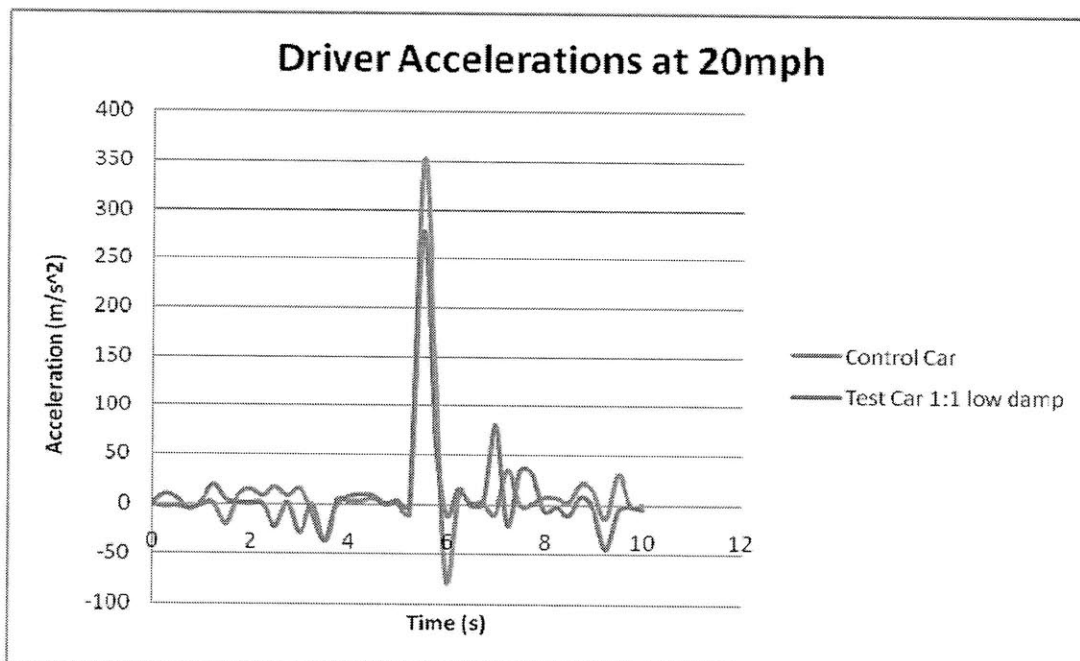


Figure 10: Car accelerations of control car and test car at 20mph

The results of the weight ratios were fairly consistent. For each run, both for the car and the driver, the 1:1 ratio resulted in the median deceleration except for in the 20mph case, where the 1:1 ratio was the lowest. The actual car had its highest deceleration in the 1:3 ratio, followed by 1:2, 1:1, 2:1, and 3:1. In contrast, for the driver, the order is reversed, with 3:1 having the highest and 1:3 having the lowest. This result varied a bit, but held true for the most part. This trend becomes very visible when looking at the average peak accelerations of the three damping levels for each weight ratio, as shown in Tables 1, 2, and 3. The charts show a clear pattern for the car and driver, where the two are inversely related. The accelerations of the car follow a concave down pattern with the given order of weight ratios, while the accelerations of the driver follow a concave up pattern.

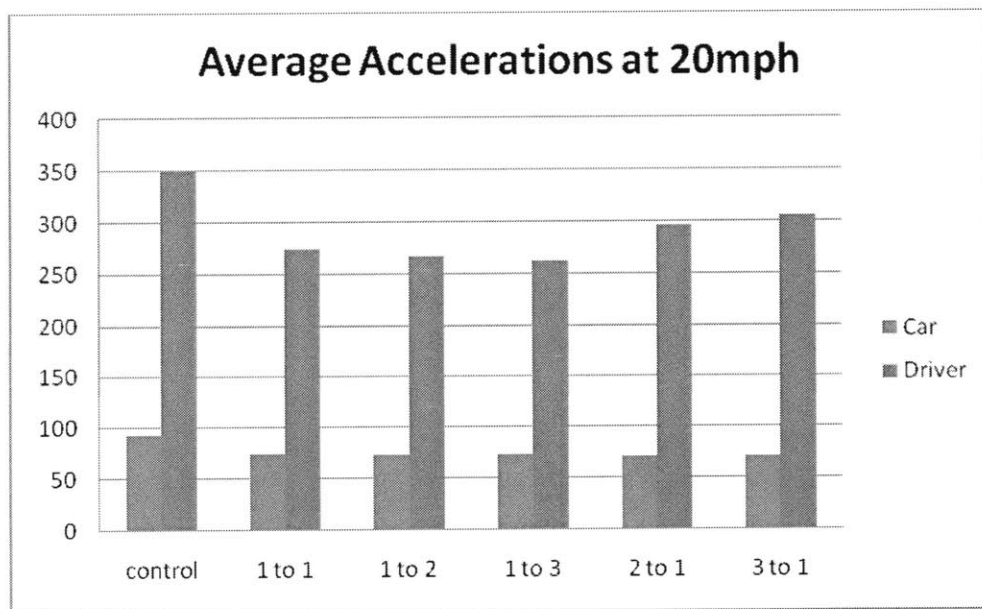


Figure 11: Average Accelerations at 20mph

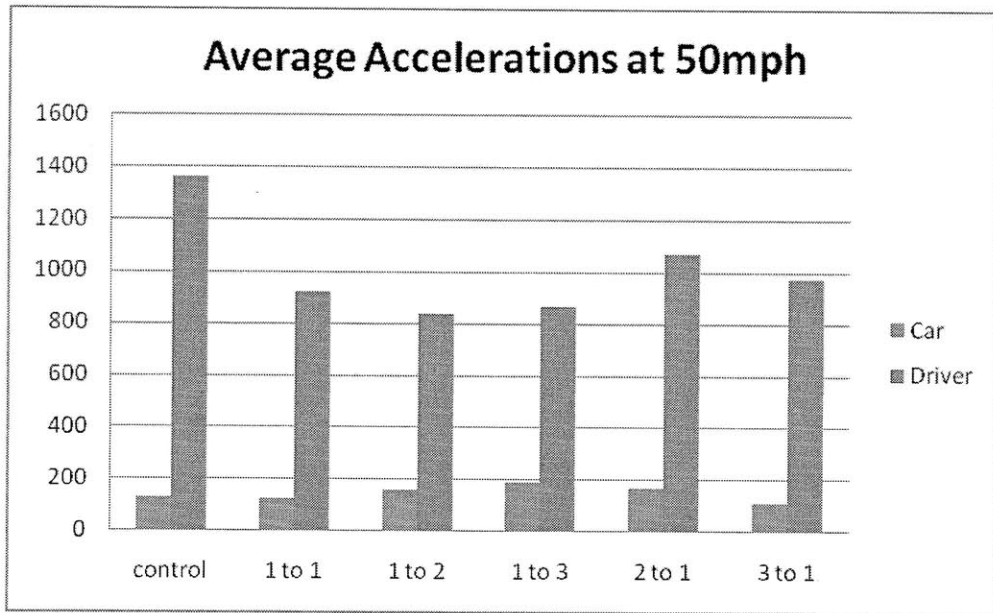


Figure 12: Average Acceleration at 50mph

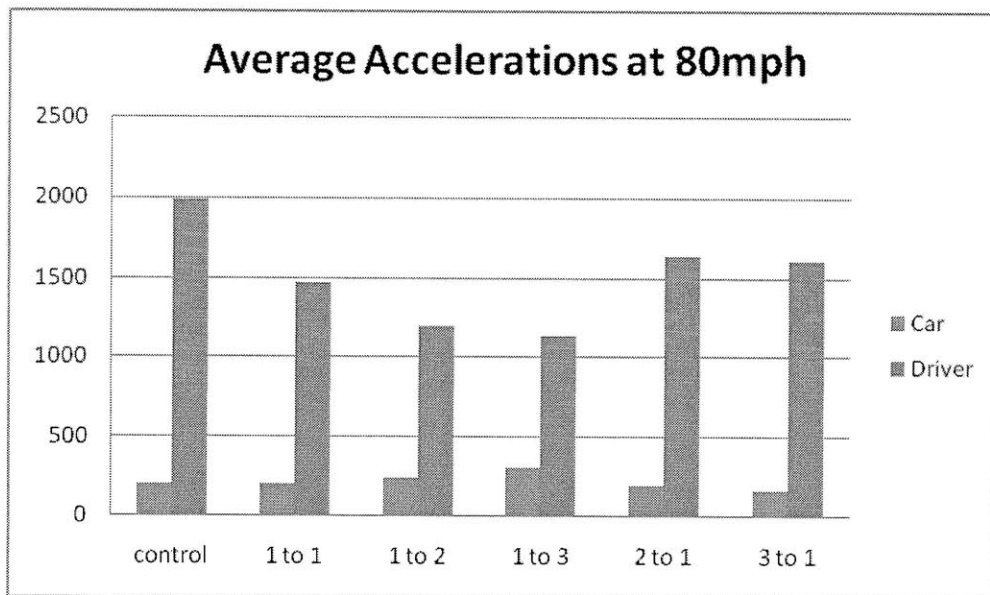


Figure 13: Average Acceleration at 80mph

For the different damping constants, the data appears very inconsistent. Figures 14, 15, 16, and 17 show the varied response for the different damping levels of a single run. As seen in the figures, the majority of the runs have lower decelerations for high or some damping. This trend is less prominent in the 20mph runs, but very clear in the 50mph and 80mph runs.

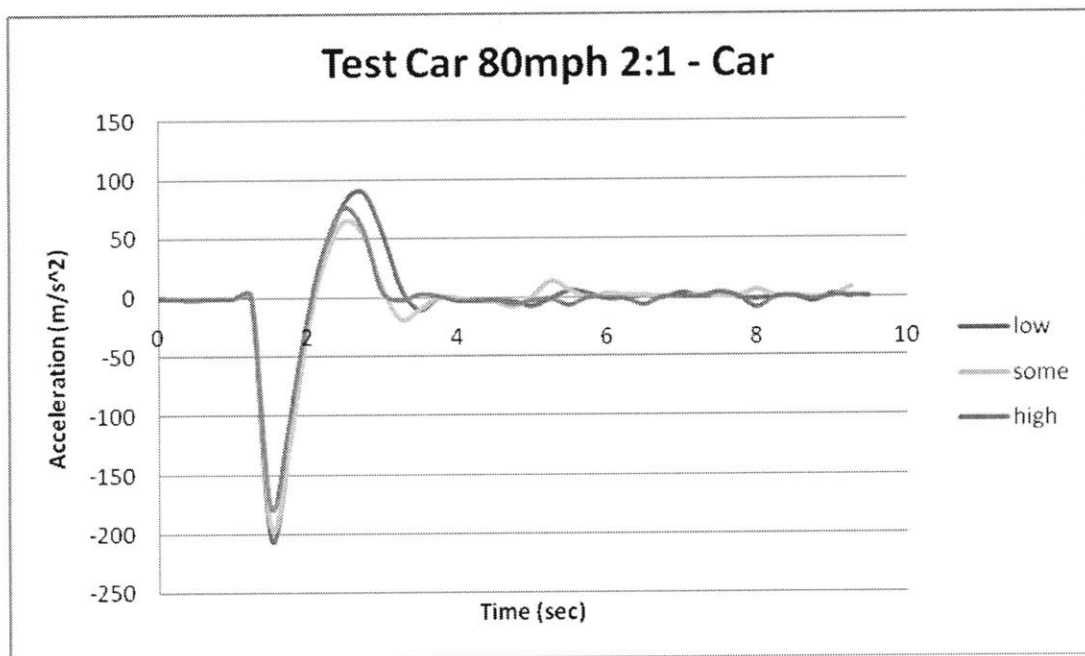


Figure 14: Test car at three levels of damping, 2:1 weight ratio 80mph

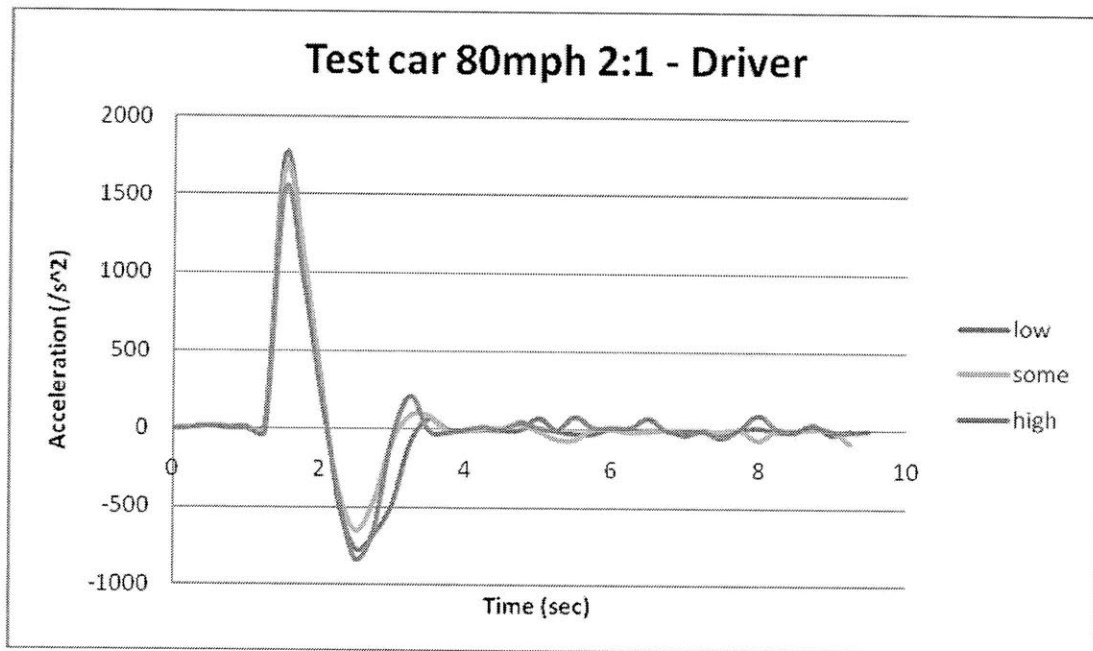


Figure 15: Test car at three levels of damping, 2:1 weight ratio 80mph

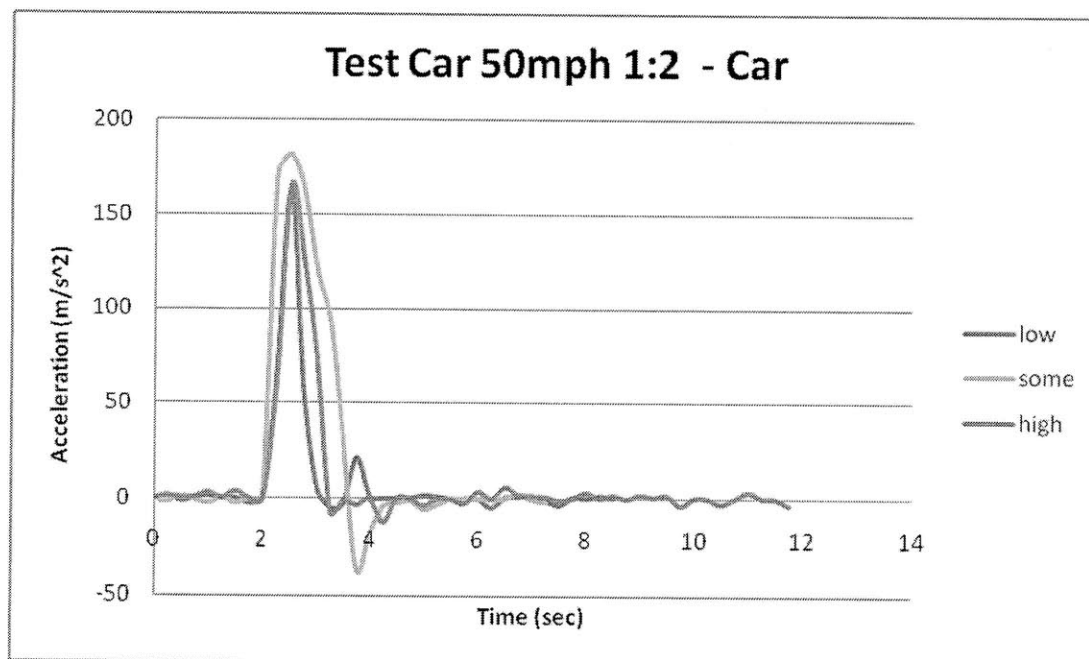


Figure 16: Test car at three levels of damping, 2:1 weight ratio 80mph

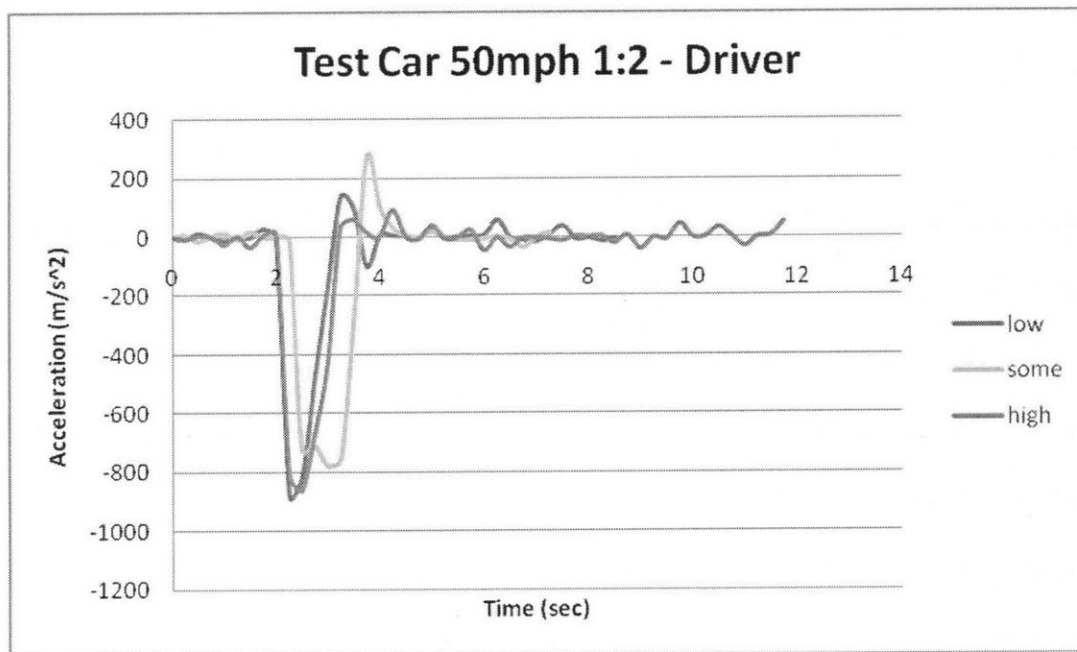


Figure 17: Test car at three levels of damping, 2:1 weight ratio 80mph

Digital Simulation: Discussion and Conclusions

The data collected from digital simulation provides a great foundation for the CityCar crash analysis. The general idea of the CityCar crash folding survives through the fact that all of the tested folding cars showed better results than that of the rigid body. However, it is important to analyze what the data means given the nature of the program, the experiment setup itself and its correlation for real life cars and the CityCar prototype.

The safe result from the experiment comes from the comparison of the test cars to the control car. The program itself cannot be treated as completely realistic due to the complications of real world dynamics as well as some of the errors seen in the program. Inconsequently, each test was done with the same discrepancies. Given that the physics modeler, in general, gives a sense of what could happen in the real world, despite some errors, it is safe to rely on the significant difference between all the test cars and the control car. This shows that, at least to some extent, the folding of the car upon collision helps to control the impact to the car and its passengers.

In contrast, the data from our varied cars is a little less trustworthy. For example, during a real crash, a car would like slam into a wall and its rear would bounce up, with little horizontal recoil. This would result in significant deformation of the car. In the simulation, the vehicle does not deform and has completely rigid components. This could explain why the test cars accelerate more with folding, even though the passenger deceleration is better. This makes it a bit difficult to predict what the effect of the weight distributions would be. It is also difficult to predict how the four bar linkage would fair in a crash, and how the damping would affect this. The hope was that the simulation would provide some idea of how the variations would impact the crash, but the data is too inconsistent to trust completely. The data would suggest that the car

should be back heavy with a considerable amount of damping in the folding process to lessen the impact on the driver, but more testing and research must be done to support this. The contrasting accelerations of the car alone would completely hinder any complete conclusion drawn from the data.

Empirical Testing: Scaled Prototype Crash Analysis

1.1-Experimental Setup

For the physical experimental setup, a 1/5 scale wooden car was built to capture the forces experienced in a head on collision. The car consisted of a four bar linkage attached to a generic body with a bumper attached to the front. A bread board holding three separate force sensors was attached to the top of the generic body (the approximate location of the passengers). A cup was placed in the front and rear compartments of the generic body to allow for slight variations in their respective weights.

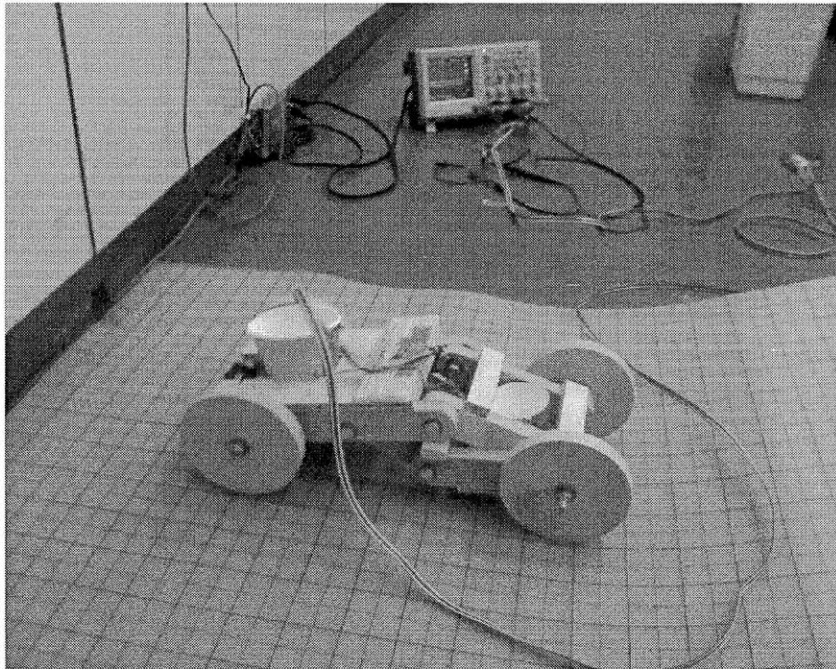


Figure 18: 1/5 Scale Car

An oscilloscope was used to record the forces measured by the force sensors. An umbilical cord was made to attach the wires on the bread board to the oscilloscope. Three

vibration sensors were used in total: a DT Series Piezo Sensor and two MiniSense 100 Vibration Sensors, one in a horizontal configuration and the other in a vertical configuration. These sensors act as cantilever beam accelerometers. Strain in the tip of the sensor creates a piezoelectric response, which is detected as the voltage output across the electrodes in the sensor.

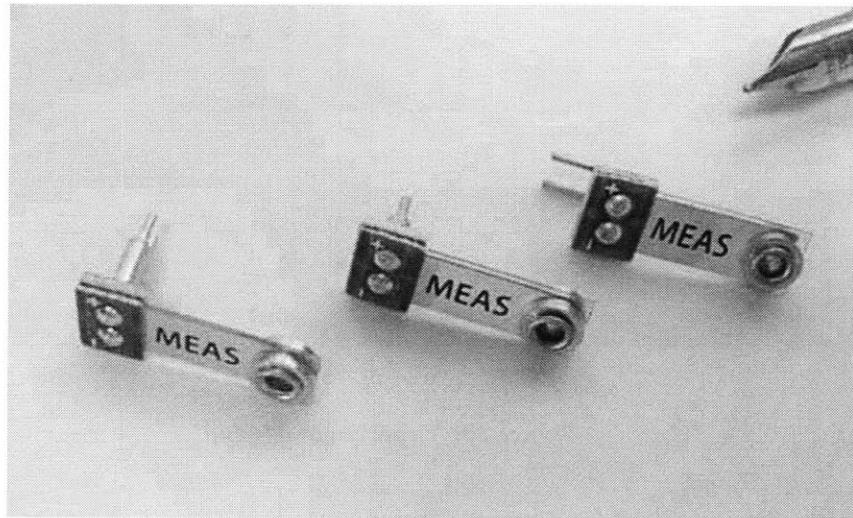


Figure 19: MiniSense 100 vibration sensors.

The physical experimental setup consists of a wooden ramp with plastic at the end of the ramp to ensure a smooth transition for the car from a declined angle to a horizontal angle. The wooden ramp was set at an angle of 18 degrees from the floor and 25" away from a wall. The plastic runner extended from the ramp to the wall to minimize the disturbances the car felt during the experimental runs.



Figure 20: Experimental Setup

1.2-Theory

In order to be able to complete several runs, the car had to be run at velocities that would not greatly damage any components of the car, mainly the four bar linkage. Without the aid of a device that applies a measured force to the vehicle at the beginning of every run, the best way to perform several runs with the least deviation in the impact velocity is to release it at fixed points on a ramp. The advantages of using a ramp are clear when examining the energy of the car in the system. At the beginning of the run, the kinetic energy of the vehicle is zero, and the potential energy of the vehicle is zero at the end of each run. Because of the relatively short distance traveled by the vehicle, the friction experienced by the wheels of the vehicle can also be neglected. With this, a simplified version of the conservation of energy equation can be used to

calculate the impact velocity of the car, yielding a velocity of 4.73 mph when released from 24” up the ramp, and 6.313 mph when released 48” up the ramp. The exact velocities do not matter in this experiment, however; the main aim of the experiment is to crash the vehicle at significantly different velocities to verify the sensors are working properly and to check for any unexpected changes in behavior in the vehicle.

1.3-Analysis

To determine whether or not the 4 bar linkage has an actual effect on the forces felt in the car by the passengers, several different parameters were varied: the car was released 24” and 48” up the ramp (corresponding to heights of approximately 9” and 16” off of the ground, respectively), the four bar linkage was ran while it was held fixed in a closed position, left loose but not held open, and left loose with a 1.5” opening (wooden block was loosely placed in the 4 bar linkage to prevent from completely closing until collision), and the car was released at its natural weight, with added weight in the front compartment, and with added weight in the back compartment (weight added in each case was 1 lb 1.7 oz). Data was collected from three separate runs for every combination of parameters.

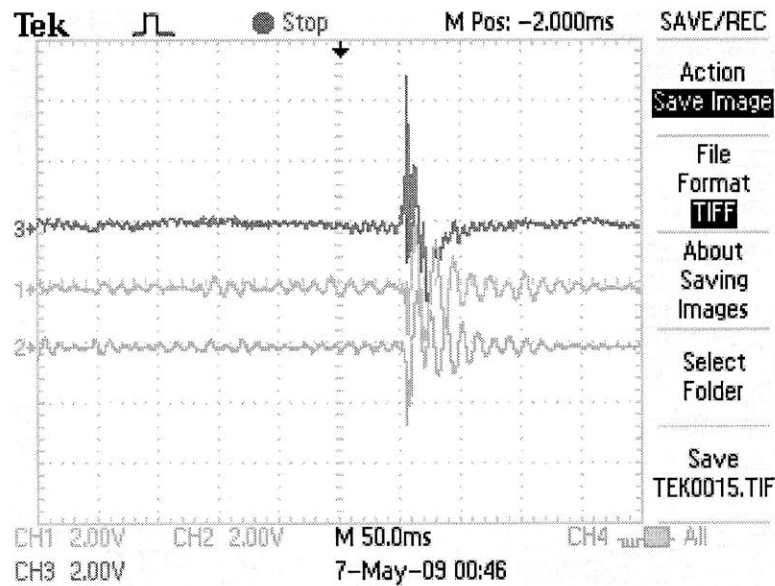


Figure 21: Raw data sample.

For the two force sensors in the vertical position, the sensitivity of the DT Series sensor was increased ten-fold to better capture the forces exerted on the car. The voltage outputs measured from this sensor were not only larger than the other sensor, but were also less precise. For our analysis, it was decided that the MiniSense 100 sensor probably had more accurate voltage outputs, so while both sensors are analyzed, the weighted sensor will be referred to more.

The voltage outputs are in the form of underdamped sinusoidal waves, which corresponds to the vibrations felt within the sensor (see Figure 5). The initial spike in the data was used as the voltage output was recorded from every graph, and average from the three runs was used in analyzing the behavior of the car. On the graphs, the purple line represented the output from the DT Series sensor, the yellow line corresponded to the MiniSense 100 vertical sensor, and the turquoise line corresponded to the MiniSense 100 horizontal sensor.

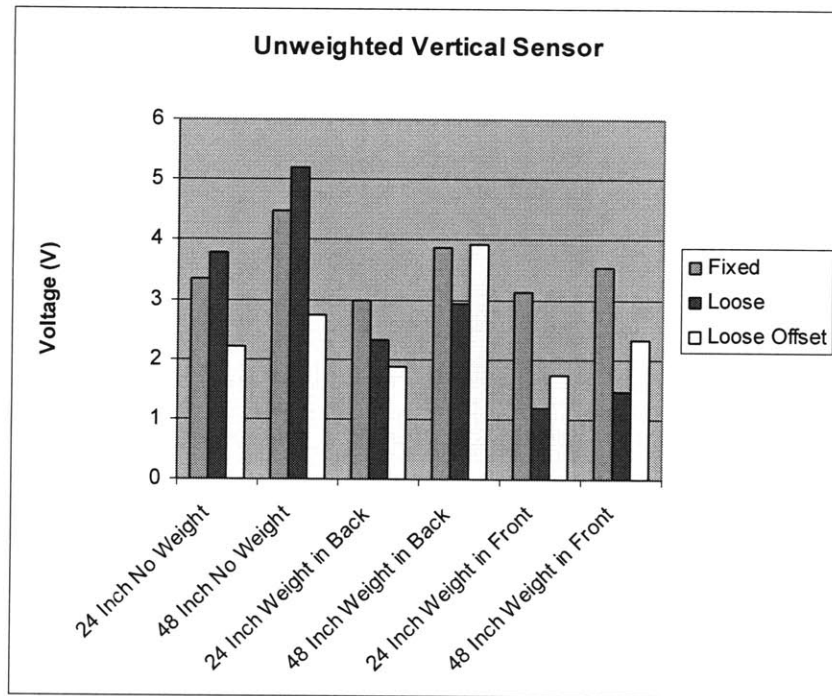


Figure 22: Graph of average voltage outputs from vertical DT Series sensor

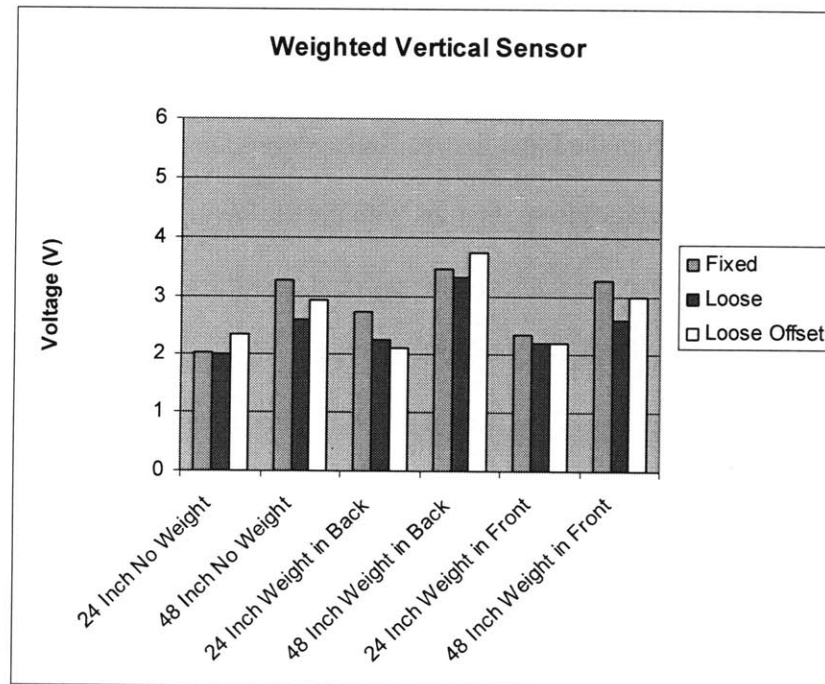


Figure 23: Graph of average voltage outputs from vertical MiniSense 100 sensor

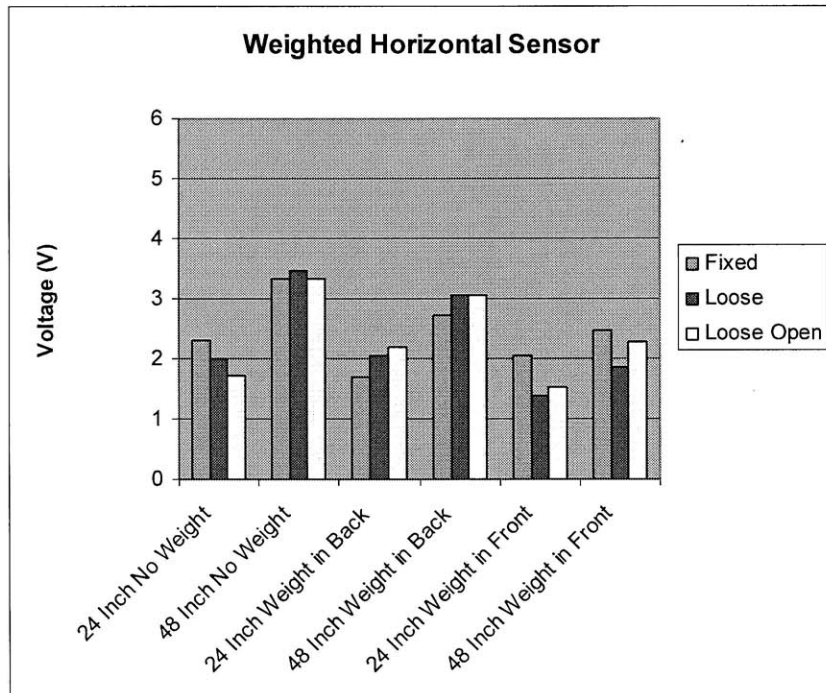


Figure 24: Average voltage outputs from horizontal Minisense 100 sensor

The data measured by the oscilloscope from the two weighted force sensors did not vary too much. The data read from the fixed four bar linkage runs averaged out higher than the non-fixed data runs, and the averages from the runs with the car having a slightly opened four bar linkage had larger forces than the runs with the unfixed closed four bar linkage. With the differing weight distributions, adding weight to the rear compartment resulted in significant increases in output voltage, but adding weight to the front compartment did not yield great differences in the output voltage.

1.4-Discussion

The results from the data supports the theory of the folding mechanism decreasing the force felt in the vehicle. The vertical sensors had voltage outputs that were for the most part

higher for the fixed linkage case than for the open linkage cases. However, there were a couple of unexpected results. The forces felt by the slightly open mechanism were actually greater than the closed unfixed mechanism. When examining this, as well as the heavier back compartment leading to an increase in the force felt, it may be possible that the back compartment impacts the front compartment and contributes to the force. A possible reason for why adding the weight to the back compartment had a much larger effect than adding it to the front is because of the different weights of the front and back compartments. The front compartment of the 1/5 scale model weighs 3 lbs 7.2 oz, while the back compartment weighs 2 lbs 5.25 oz, so adding the weight in the back causes a 47.52% increase, while adding the weight to the front results in only a 32% increase in weight. This also changes the back to front weight ratio of the car; it is approximately 2:3 in its natural state, 1:1 when the weight is added to the back compartment, and 1:2 when the weight is added to the front compartment. Having a large increase in

Implications of Testing on Proposed Design

Overall, the simulated and empirical testing helps to provide a very simple, clear cut conclusion: folding the CityCar during a crash will decrease the impact force. There are several other factors that go into this process, some of which were considered in this project. The simulation attempts to analyze how the weight distribution relates to the process, and how damped the folding process should be. The empirical testing addresses how well the car would crash in a real world crash, how easily it needs to be able to open, and how damped the process should be as well.

Nevertheless, all that can be concluded from the data is that the folding helps. The Working Model program is not realistic enough to account for all the factors that would be present in the real world and the actual car. The empirical test was done with a wood car, so the testing on that can only go so far. On the bright side, the testing provides a great view of what needs to be considered next. One thing is how the folding process be initiated in the crash. Too much force could compromise the folding action unless the car opens some before impact. This will need to be tested. Along with this is to figure out how much the folding process needs to be damped. In order for the folding to provide significant help, some damping would have to be in place. The car cannot fold too easily, however, a car hard to fold would start to defeat the purpose. Weight distribution should be considered as well. The digital testing suggests that the weight ratio plays an important part, though this contribution may be unclear in the data. It will also add to how the car deforms, and the impact felt from the completion of the folding.

All in all, the folding of the CityCar proves to be a promising idea. In comparison to today's safety standards and crash parameters for existing vehicles, testing on the actual prototype will need to be done to see if it can compete. The testing in this project provides as an

indication as to the whether or not the idea holds promise at all. Based on the results of the digital simulations and the wooden model of the CityCar, the answer to this question will be yes. Hopefully this document will provide as a good basis for future testing on the CityCar final prototype in the event of a collision.

Acknowledgements

We would like to thank Professor William Mitchell for allowing us to work on the frontal crash analysis of the CityCar, and Will Lark for aiding us greatly in our work and taking a lot of time out of his own full schedule to ensure our success.

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